IN SITU RADIATION MAPPING FOR ASSESSMENT OF DISTRIBUTED RADIOACTIVE CONTAMINATION

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ABSTRACT

The practice of in situ radiation mapping is examined as a method for characterizing the distribution of extended sources of radioactive material. High speed radiation detectors permit dense mapping over large areas using continuous data collection during detector scanning. In two presented examples, high fidelity map images provide detailed information on radioactive source distribution that reveals the location of hot spots and outer contamination boundaries as well as suggesting the mode of contaminant deposition. Comparisons between in situ mapping data and conventional sampling results reveal differences in the amount of averaging that occurs over small scale heterogeneities. Quantitative methods for estimating source distribution and for converting in situ measurements into radionuclide concentration estimates further extend the usefulness of the method.

I. INTRODUCTION

The term in situ radiation mapping refers to the practice of scanning a radiation sensor over a surface suspected to contain radioactive materials, such as the ground, so that spatial variations of the radiation field may be measured. A detailed image of the radiation field variation is obtained by simultaneously recording the position of the radiation detector during repeated measurements of the radiation field and inputting these data into standard mapping software packages. The method has utility in many situations where soil sampling or hand held detector surveys are currently used, such as in characterization of radioactively contaminated sites including characterization during and after remedial excavations. Various approaches have been used to conduct in situ radiation surveys including motorized vehicles, manually pushed carts, remotely controlled trolleys, heavy construction equipment, and even a fork lift. In all cases the purpose is the same: to obtain high fidelity radiation maps that may be used to infer the position and amount of radioactive material present.

II. WORK DESCRIPTION

Typical in situ radiation surveys employ high speed radiation sensors based on large detectors or linked detector arrays. Large detector areas produce excellent sensitivity with short counting times, as small as one second in duration. With this sensitivity, in situ mapping detectors may be operated continuously while in motion and still measure spatial variation of the ambient radiation field in great detail. As an example, a detector deployed from a vehicle moving at 1.5 m/s (5 ft/s) will collect a 1.5 m x 1.5 m (5 ft x 5 ft) grid (>1700 points) of independent radiation field measurements at a 1 acre site in about 30 minutes. Radiation measurements may be displayed in map form as they are collected giving immediate information on the field variation and the location and relative significance of radiation hot spots. The information, though qualitative, offers greatly improved assessment of the overall contamination conditions compared with conventional methods.

Over the last five years, the Idaho National Engineering and Environmental Laboratory (INEEL) has developed high speed radiation detectors, sensor deployment equipment, and data analysis techniques to support in situ radiation mapping operations. The mapping equipment has been used at a number of radioactively contaminated sites including a 55 gallon barrel storage facility at INEEL, remedial excavation sites at Mound Plant and Savannah River Site, and soil contamination areas at INEEL and Mound Plant.[1,2,3,4] These measurement programs have targeted high and low energy gamma-ray emitting radionuclides as well as neutron emitting radionuclides.

Two examples of mapping results are presented to illustrate the unique information content obtained by high fidelity mapping. This is followed by a brief discussion of qualitative and quantitative issues inherent to in situ mapping applications. In particular, we examine the relationship between in situ mapping results and results obtained by conventional sampling and analysis.

III. RESULTS

A large area in situ radiation survey conducted at the Idaho National Engineering Laboratory's ARA-23 site reveals some of the advantages of in situ mapping (Figure 1). This survey encompassed over 40 acres of open sagebrush plain surrounding the site of a 1961 reactor accident. The principal contaminant at ARA-23 is Cs-137, which emits a high energy (661 keV) gamma-ray. Radiation maps were produced from nearly 70,000 in situ measurement data points collected using two 1200 cm^2 plastic scintillation detectors mounted on an all-terrain vehicle equipped with GPS navigation.[4] In addition, in situ Ge-spectrometer measurements were obtained in areas inaccessible to the vehicle and to serve as calibration points.

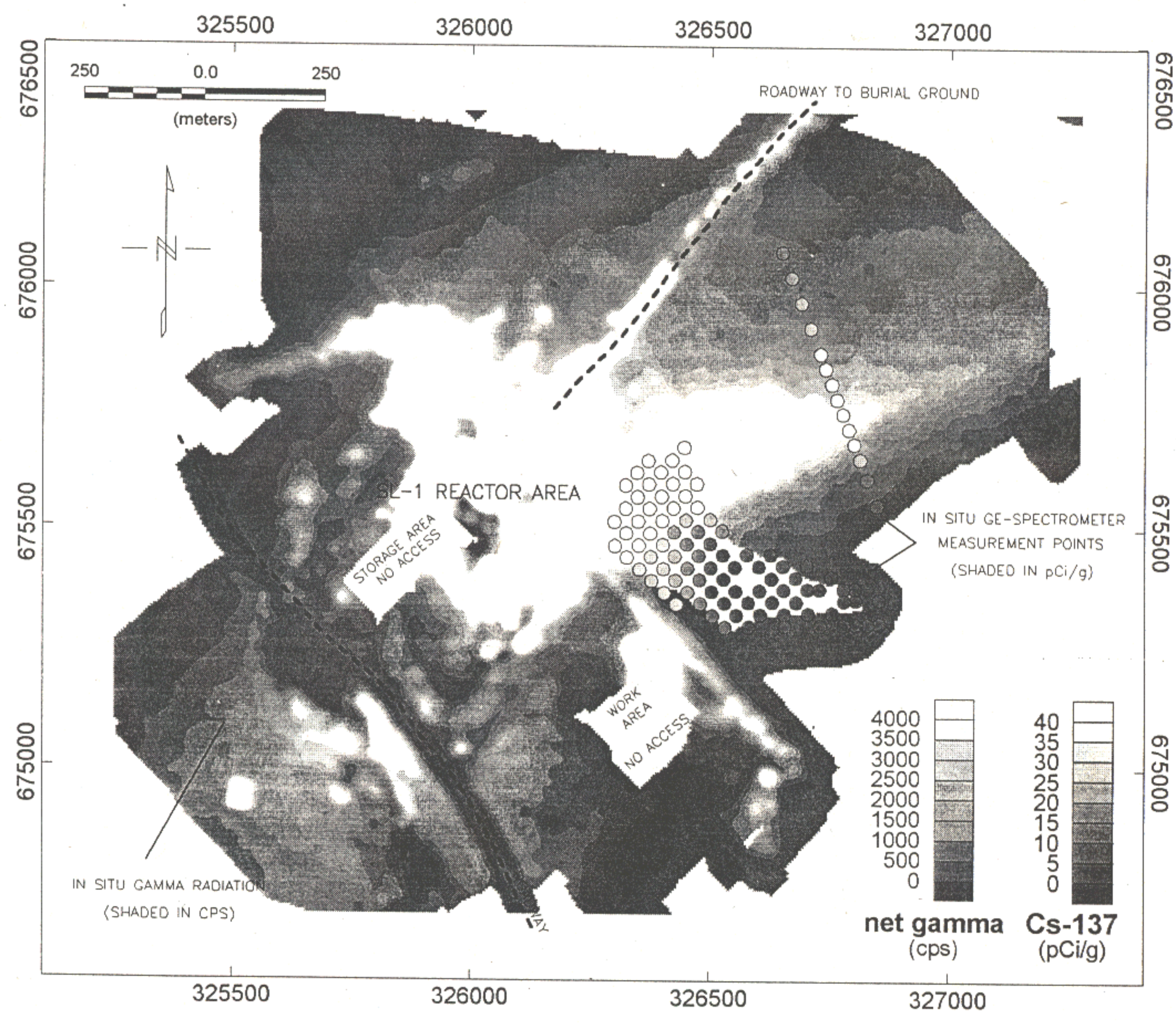

Figure 1. *Map showing in situ radiation measurements collected at the ARA-23 site on the Idaho National Engineering and Environmental Laboratory. The map shows both in situ bulk gamma radiation measurements collected using a plastic scintillation detector and in situ 661 keV gamma ray measurements collected using a Ge-spectrometer.*

The Figure 1 map clearly shows a) high radiation areas near the former reactor facility, b) numerous local hot spots, c) a windward radioactive soil plume extending northeast across the desert, d) contamination on a roadway used during transportation of soil and debris to a burial area, and e) a recently constructed “clean” roadway.

In the second example (Figure 2), in situ radiation mapping was performed during remedial excavation of Pu-238 soil contamination at the Miami-Erie Canal adjacent to DOE Mound Plant in Ohio. A series of radiation maps were acquired during two successive excavation levels over a portion of the canal bed. Measurements were made using a low energy gamma-ray detector built from six 7.5 cm x 7.5 cm (3 in x 3 in) thin film calcium fluoride (CaF_2) crystals. The CaF_2 detector was deployed by the INEEL Warthog excavation monitoring system, which attaches to a standard heavy duty excavator and permits mapping scans to be made without human entry onto the site.[5]

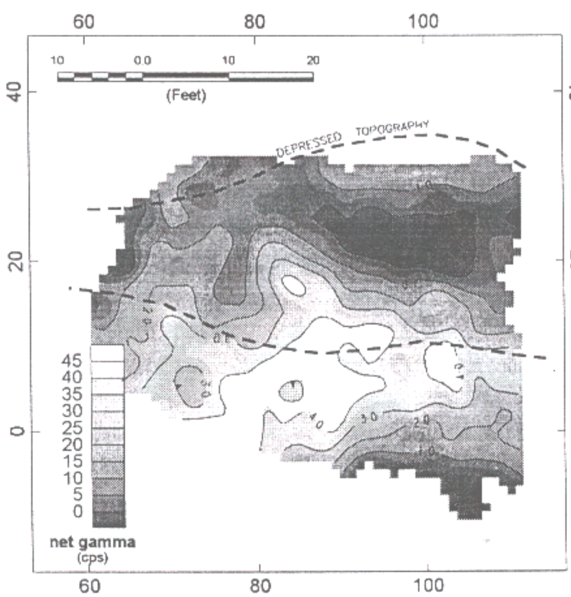

***Figure 2a.** In situ radiation measurements collected at DOE Mound Plant ‘s Miami-Erie Canal prior to excavation.*

The Figure 2 map sequence gives a three dimensional representation of the Pu-238 soil plume and several conclusions may be drawn by inspection. Pu-238 contamination is concentrated along a linear trend. The level of contamination increases with depth, but stays roughly in the same horizontal position. Topography data collected simultaneously with CaF_2 data show that the contamination trend does not correspond with the depressed canal bed, suggesting that deposition occurred by some means other than water transport.

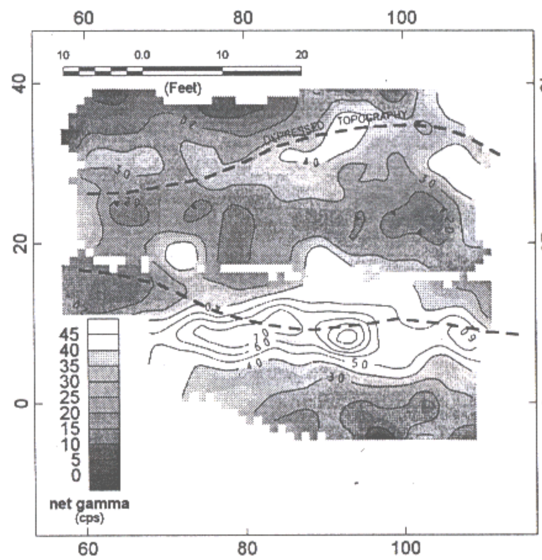

***Figure 2b.** In situ radiation measurements collected after excavation of 0.3 –1.0 m (1–3 ft) of soil*

In these examples, mapping results a) reveal high fidelity details of the contaminant distribution that give insight into the mode of deposition, b) show the precise position and relative size of hotspots, c) give clear indications of the outer boundary of contaminated areas, and d) provide a high level of confidence that no contamination has been “missed” because of the completeness of data coverage.

IV. COMPARISON WITH SAMPLING

During development of in situ radiation mapping techniques there have been numerous opportunities to compare in situ mapping results to site sampling data acquired to obtain similar information on contaminant distribution. Indeed, this comparison addresses a crux issue for those considering the use of in situ measurements to complement or replace portions of their site sampling programs.

Figure 3 shows a compilation of results from three in situ radiation surveys, plastic scintillation detector surveys for Cs-137 at INEEL ARA site and at Savannah River, and a CaF_2 detector survey for a Pu-238 survey at Mound Plant.5 The chart shows a crossplot between sampling results (in pCi/g) and in situ detector measurements (in cps) at common locations.[3]

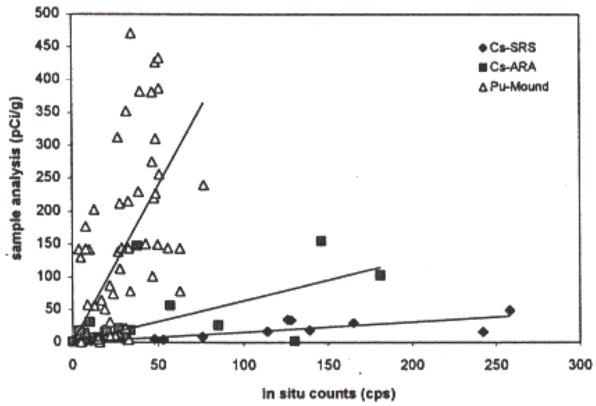

Figure 3. *Crossplot between in situ measurements and sampling results for three different detectors at three different sites as indicated*

Differences in detector sensitivity are reflected by the steepness of the crossplot trendlines. Even for the low sensitivity CaF_2 detector, Figure 3 shows good correlation between sampling and in situ measurements, i.e. samples collected in high radiation areas tend to show higher contamination levels. However, significant excursions from ideal correlations are evident.

The excursions from ideal correlation undoubtedly result in part from small scale heterogeneity in contammant distribution. Whereas sampling produces a concentration value typically based on a few hundred cubic centimeters of soil, in situ detectors are sensitive to several thousand to several hundred thousand cubic centimeters of soil centered beneath the detector. Thus the in situ detector produces an average or "bulk" measurement that fails to capture detailed variations. Sampling captures these variations at a particular location but it becomes difficult to confidently extrapolate between widely spaced sampling points. The two methods agree closely in areas where contamination is relatively uniform.

V. QUANTITATIVE METHODS

As has been discussed in a companion paper in this session, estimates of in situ radionuclide concentration can be made subject to two assumptions: 1) radiation above background is due to a single, known contaminant (or group of contaminants occurring in known ratios), and 2) the distribution of the contaminant(s) throughout the detector's volume of investigation is known at each measurement point.[6] Assumption 1 can usually be established from sampling results or from in situ measurements using a gamma-ray spectrometer. Assumption 2, which depends on knowledge of both the area and depth distribution of the contaminant, can be more difficult to establish.

The in situ mapping data themselves are ideally suited for assessing a contaminant's area distribution. Each radiation detector has a system response for a true point radiation source that may be determined from laboratory measurements. The system response is characterized by its Full Width at Half Maximum ($FWHM_{SYS}$) dimension (Figure 4).[7]

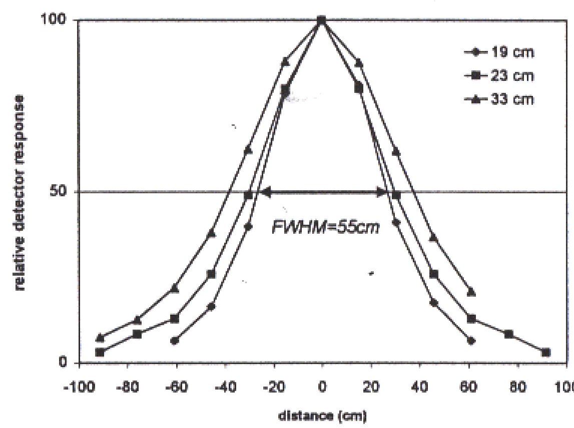

Figure 4. System response for a plastic scintillation detector measured at various distances from a point source as indicated

The area extent of a radiation field anomaly measured during an in situ survey may be compared against the sensor $FWHM_{SYS}$ to assess the actual distribution. If the measured $FWHM_{MEAS}$ exceeds the system response $FWHM_{SYS}$, we may conclude that the radioactive material is not a true point source, but is distributed over an area approximately equal to the length D given by

$$D = FWHM_{MEAS} - FWHM_{SYS}$$

as shown by the examples in Figure 5. When D exceeds the diameter of the sensor field of view (0.5 m to about 5 m depending on the detector size, shielding, and height during measurement), the contaminant may be treated as areally continuous for purposes of calculating concentrations .

The chief problem in converting in situ radiation measurements into concentration estimates arises from uncertainty in the depth distribution of the contaminant. Sample results provide little help since most sampling programs do not produce detailed information on contaminant depth distribution within the first few inches of soil. Spectral measurements of some radionuclides can provide control on the depth to the top of the contamination layer based on differential attenuation of gamma-rays having different energies. Depth to the bottom of the contamination is the most difficult parameter to establish although a particular detector's effective depth of investigation provides a lower limit on this depth. When necessary, specialized sampling protocol can be designed to evaluate the lower depth limit of contamination in detail. At excavation sites, repeated in situ mapping at regular depth intervals will often reveal a depth distribution pattern.

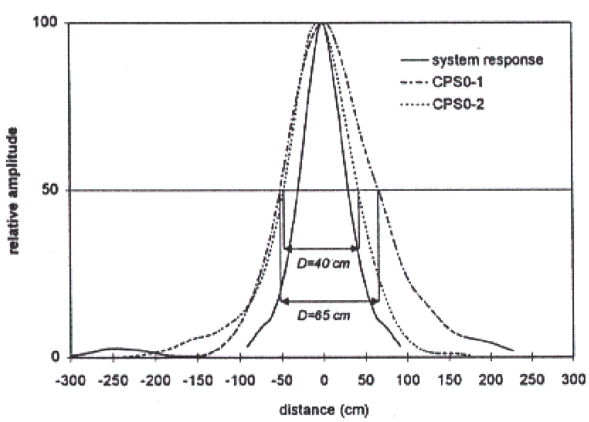

Figure 5. *Examples of using the FWHM method to assess the size of a radioactive source. Mapped anomalies CPS0-1 and CPS0-2 have the approximate horizontal dimension indicated*

Once a contaminant distribution model is adopted, a calibration methodology is developed to convert the sensor counting rate to an activity concentration in pCi/g (or, for surface distributions, pCi/cm^2). Several methods may be used to establish this calibration relationship. The adopted contaminant distribution model may be input into a Monte Carlo simulation program that accounts for the detector geometry and energy response curve to obtain a mathematical relationship between concentration and detector counts. Alternatively, a calibration area may be established somewhere within the in situ survey area. Samples or in situ Ge-pectrometer measurements are used to determine radionuclide concentration at many points within the calibration area. In situ measurement data are then calibrated to the sample results by linear regression techniques (Figure 6).[3,4]

After conversion, the data are used to produce maps of "apparent" activity concentration. Activity concentration maps can be extremely useful in defining limits for remediation activities that depend on concentration levels since they permit these boundaries to be drawn in far greater detail than is possible from widely scattered sampling results. It must, however, be remembered that the usefulness of these estimates depends on the correctness and uniformity of the adopted contaminant distribution model. Boundaries drawn based on apparent concentration estimates may shift depending on the model, particularly where the boundaries lie within zones having uniform or gradually varying concentration (Figure 7).[3]

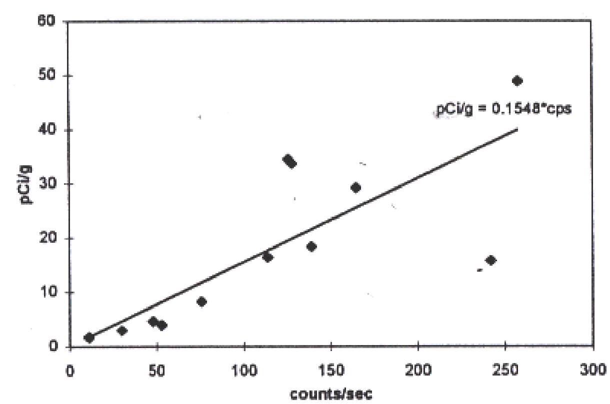

Figure 6. Linear regression to determine calibration factor for converting in situ counts/sec into concentration estimates in pCi/g.

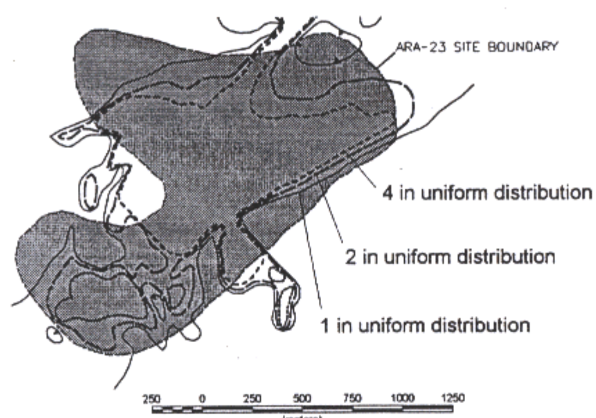

Figure 7. Limit of Cs-137 contamination exceeding 17 pCi/g based on three different depth distribution models as shown.

Future development of quantitative analysis techniques can extend the value of in situ mapping programs. Extended source modeling is one important area of future research. The spatial variation of radiation fields may be used to analyze the nature of extended source distributions in the same way that the $FWHM_{SYS}$ is used to determine if a particular radiation field anomaly is due to a point source. Certain types of extended source geometries, e.g. dipping or truncated layers will produce characteristic radiation field patterns. vi These source distributions can be easily modeled to produce characteristic “type curves” that can serve as templates for interpreting in situ mapping data. In the future it should be possible to investigate in situ data sets through direct iterative modeling of 2-D and 3-D source geometries. Many of the principles and tools governing this process have been developed for geophysical interpretation and may be readily adapted to radiation measurements.

VI. CONCLUSIONS

In situ radiation mapping has clear benefits as a contaminated site assessment tool. Foremost among these benefits is the ability to rapidly produce detailed information on the spatial distribution of radioactive contamination over large areas. Mappmg methods quickly identify hot spots, show patterns of contaminant deposition and leave no significant data gaps. In situ measurements agree well with sampling results but have the advantage of averaging through small scale concentration heterogeneity. Map analysis techniques can be used to differentiate between point and extended source distributions. Quantitative analysis methods permit estimates of in situ activity concentrations that may be used to define boundaries for remedial activities. Continuing research on quantitative analysis methods could lead to more rigorous use of in situ radiation mapping data.

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